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SPACE VEHICLE
DESIGN CRITERIA
(ENVIRONMENT)

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SOLAR ELECTROMAGNETIC RADIATION

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FOREWORD

NASA experience has indicated a need for uniform design criteria for space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidances and Control
Chemical Propulsion

Individual components are issued as separate monographs as soon as they are completed. A list of monographs published in this series can be found on the last page.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that the monographs will be used to develop requirements for specific projects and be cited as the applicable documents in mission studies, or in contracts for the design and development of space vehicle systems.

This monograph replaces an earlier monograph on the same subject published in 1965. The current document was prepared under the cognizance of the NASA Goddard Space Flight Center (GSFC) with S.A. Mills and J.J. Sweeney of GSFC serving as program coordinators.

Dr. M.P. Thekaekara of GSFC was the principal author and chairman of the Advisory Panel which developed the solar constant and solar spectrum presented herein. The following individuals served as panel members:

A.J. Drummond	Eppley Laboratory
D.G. Murcray	University of Denver
P.R. Gast	AFCRL (retired)
E.G. Laue	Jet Propulsion Laboratory
R.C. Willson	Jet Propulsion Laboratory

Comments concerning the technical content of these monographs will be welcomed by the National Aeronautics and Space Administration, Goddard Space Flight Center, Systems Reliability Directorate, Greenbelt, Maryland 20771.

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SOLAR ELECTROMAGNETIC RADIATION

1. INTRODUCTION

Knowledge of solar electromagnetic radiation is needed in space vehicle design to establish the thermal balance of the spacecraft. For orbits near the Earth or other planets, the planetary albedo and emitted radiation also have to be taken into account to achieve thermal balance. These values depend on solar radiation, the primary source of energy. Thermal balance can be upset during a mission if ultraviolet radiation degrades spacecraft surfaces.

Ultraviolet radiation also may be detrimental to the mission by damaging insulation materials and optical elements. In plastics there can be a degradation of mechanical properties, both embrittlement and softening; there can be discoloration with attendant changes in such optical properties as absorption, emittance, and transmittance; and there can be changes in electrical properties.

For some experiments aboard meteorological satellites, knowledge of solar radiation is needed so that the Sun's energy can be used as the standard of comparison for determining the Earth's albedo. Precise prediction of the output of solar cells also requires knowledge of the solar spectrum.

Solar radiation can be a factor in the design of spacecraft attitude control systems because of solar radiation torques which are the subject of a related design criteria monograph (ref. 1). Another related monograph is being developed which will adopt values for the Earth's albedo and emitted radiation.

This monograph replaces a design criteria monograph published in 1965 on solar electromagnetic radiation (ref. 2). It gives new values for the solar constant and solar spectral irradiance. High-altitude observations with aircraft, balloons, and spacecraft have made possible improvement over the values given in the previous monograph, which depended upon ground-based observations.

2. STATE OF THE ART

The spectrum of the Sun extends from X-rays of wavelength 1 Å or below to radiowaves of wavelength 100 meters and beyond. Measurements have been made in recent years to cover the entire range, but consideration of a lesser range is usually sufficient for most applications of engineering and technology. Ninety-nine percent of the solar energy is in the range 0.276 to 4.96μm, and 99.9 percent of the solar energy is in the range of 0.217 to 10.94μm.

Solar electromagnetic radiation usually is described in terms of the solar constant and solar spectral irradiance. The solar constant is the amount of total radiant energy received from the Sun per unit time per unit area exposed normally to the Sun's rays at the mean Sun-Earth distance in the absence of the Earth's atmosphere. Solar spectral irradiance is the distribution of the same energy as a function of wavelength.

2.1 Solar Constant

2.1.1 Ground-Based Measurements

Extensive ground-based measurements have been made for over half a century to determine values for the solar constant. The large uncertainties inherent therein are discussed in references 3, 4, and 5.

Table I lists the results of some of the major attempts which have been made. The values cover a rather wide range, 132.3 to 143.0 mW cm^{-2}. They are referred to different scales of radiometry, and the scales have not remained constant over the years. Some of the authors, especially the earlier ones, quote the value in units of calories cm^{-2} min^{-1}. The conversion to mW cm^{-2} is made on the assumption that the mechanical equivalent of heat, J, is 4.1840 joules per calorie (ref. 6). The joule is the absolute joule and the calorie is the thermochemical calorie; this conversion factor constitutes the definition of the thermochemical calorie.

For values of the solar constant derived from ground-based measurements such as in table I, the area under the spectral curve is integrated and corrections added for ultraviolet (UV) and infrared (IR) which cannot be measured from the ground. Techniques of measurement and data analysis vary considerably from one author to another. Surveys of the literature of the solar constant are given in references 4, 7, 8, 9, and 10.

Four of the values in table I have been selected for special comment because they have received wide recognition.

2.1.1.1 Johnson Spectrum

The value 139.5 mW cm^{-2} or 2.00 cal cm^{-2} min^{-1} proposed in 1954 by F.S. Johnson was widely considered as definitive until recent years and formed the basis for the first NASA design criteria monograph on solar electromagnetic radiation (ref. 2).

Johnson's value was based mainly on a revision of the measurements made earlier by the Smithsonian Institution of Washington, D.C. (refs. 11, 12, and 15) with modifications in the visible spectrum on the basis of Dunkelman and Scolnik (ref. 10) and in the ultraviolet portion of the spectrum from rocket data (ref. 21). The Johnson value is higher than the Smithsonian values, partly because he raised the absolute scale of Dunkelman and Scolnik by six percent to match the curve to Moon's at 0.6μm plus an additional 2.8 percent to match the Smithsonian absolute energy scale. Accordingly, the area under the Johnson

Table I

Evaluations of the Solar Constant
Derived From Ground-Based Measurements

Investigators	Year	Solar Constant mW cm^{-2}
P. Moon (ref. 11)	1940	132.3
L. B. Aldrich and C. G. Abbot (ref. 12)	1948	132.6
W. Schüepp (ref. 13)	1949	139.2
M. Nicolet (ref. 14)	1951	138.0
L. B. Aldrich and W. H. Hoover (ref. 15)	1952	135.2
R. Stair and R. G. Johnston (ref. 16)	1954	142.8
F. S. Johnson (ref. 17)	1954	139.5
C. W. Allen (ref. 18)	1958	138.0
P. R. Gast (ref. 19)	1965	139.0
R. Stair and H. T. Ellis (ref. 20)	1968	136.9
D. Labs and H. Neckel (ref. 7)	1968	136.5
E. A. Makarova and A. V. Kharitonov (ref. 8)	1969	141.8

curve from 0.22 to 0.70μm is 68.1 mW cm^{-2} as compared to the area under the curve adopted by this monograph of 63.3 mW cm^{-2}.

2.1.1.2 Other Spectra

In the solar spectrum between 0.31 and 0.53μm Stair and Ellis (ref. 20) made direct measurements, referenced to the spectral irradiance lamps calibrated at the National Bureau of Standards. They revised the Johnson curve downward in this range but assumed the Johnson curve for the longer wavelengths. Then the solar constant was obtained by integrating the area under the curve.

Labs and Neckel (ref. 7) measured continuum intensities at the center of the measured solar disc between 0.33 and 1.25μm, made corrections for limb darkening and Fraunhofer absorption, and added spectral data from other sources to obtain the energy integral.

The final value in table I (ref. 8) is among the highest because of the weight given the observational data of Makarova (ref. 22) and of Sitnik (ref. 23) which yielded relatively higher spectral irradiance values in the visible and near IR ranges of the spectrum.

2.1.2 High-Altitude Measurements

Table II lists eight values of the solar constant which were obtained from the following high-altitude observing platforms: jet aircraft flying at about 12 km, balloons at 24 km and 31 km, the X-15 rocket aircraft at 82 km, and the Mariner Mars spacecraft totally outside the Earth's atmosphere.

2.1.2.1 Galileo Experiment

The first four values listed in table II are from the Galileo experiment aboard the high-altitude research aircraft, NASA 711 (refs. 5, 24, and 25). At the flight altitude, the atmosphere above the aircraft was 21 percent of that at ground level. The average water vapor content above the aircraft was about 20μm of precipitable water (about 0.1 percent of 17.9 mm, the amount of precipitable water averaged for the whole atmosphere and the whole year for mean latitudes) (ref. 26). During each of the six flights, the instruments were pointed at the Sun for 2½ hours.

Table II

Evaluations of the Solar Constant
Derived from High-Altitude Measurements*

Platform (Detector)	Year	Solar Constant (mW cm^{-2})	Estimated Error (± mW cm^{-2})
NASA 711 Aircraft (Hy-Cal Pyrheliometer)	1967	135.2	2.2
NASA 711 Aircraft (Ångström 7635)	1967	134.9	(4.0)
NASA 711 Aircraft (Ångström 6618)	1967	134.3	2.6
NASA 711 Aircraft (Cone Radiometer)	1967	135.8	2.4
Murcray Balloon (Pyrheliometer)	1969	133.8	0.6
Soviet Balloon (Actinometer)	1970	135.3	1.4
Eppley-JPL High-Altitude Aircraft (Pyrheliometer)	1968	136.0	1.3
Mariner 6 and 7 Spacecraft (Cavity Radiometer)	1969	135.3	1.0

* The scale of radiometry is the International Pyrheliometric Scale (IPS 56) for the Ångströms, pyrheliometers and actinometer; the black body scale for the Hy-Cal; and the scale of absolute electrical units for the cone and cavity radiometers.

References 5, 24, and 25 provide additional information, including the method adopted for extrapolation to zero air mass and corrections for ozone and aircraft window transmittance.

2.1.2.2 Balloon Measurements

At balloon altitudes the water vapor of the atmosphere is not a major source of uncertainty. The atmosphere above a balloon at 31 km is only about 1 percent of the total. Balloon data are available from two independent sources, Murcray and Kondratyev. Murcray's four series of flights used pyrheliometers (refs. 27 and 28) which gave values fairly close to each other although they are low compared to the data from other high-altitude measurements. The value given by Kondratyev et al. is based on balloon measurements made with actinometers in the USSR from 1961 to 1968 (refs. 29 and 30).

2.1.2.3 The Eppley-JPL Experiment

Between July 1966 and August 1968, total irradiance data were assembled and analyzed for 14 selected series from 17 flights of NASA research aircraft, including the B-57B, Convair 990, and X-15 (refs. 31, 32, 33, 34, and 35). Among these flights the USAF/NASA rocket X-15 flight of October 17, 1967 first provided measurements well above the ozonosphere. The lower level jet aircraft flights into the stratosphere were frequently accompanied by simultaneous ground-based measurements of total ozone concentration at nearby locations. Relevant water vapor content above the aircraft was measured either by balloon radiation sonde or through the use of infrared emission measurements on the aircraft. The aircraft measurements were then corrected for Rayleigh scattering, water vapor, ozone absorption, and for the mean Earth-Sun distance.

The radiometer, which is described fully in reference 34, was a 12-channel model incorporating fast response, high sensitivity, and wirewound-plated thermopile sensors. Ten of the channels were optically filtered; quartz lenses were used for the narrow bandpass channels. The results of the filter measurements are given in section 2.3.2.2.

2.1.2.4 JPL Mariner Data

Measurements from the JPL Mariner 6 and 7 Mars missions were made by absolute cavity radiometers (ref. 36). Although measurements from the two spacecraft were made in widely-separated locations in space, they gave values which were in close accord when reduced to 1 AU. A large mass of data was obtained during a period of five months.

2.2 Solar Spectral Irradiance

Numerous attempts have been made to map out the spectrum of the Sun from the ground for different values of solar zenith angle and to determine by extrapolation the spectral irradiance. All the ground-based values of the solar constant in table I are integrals of the area under the spectral curve and hence presuppose a spectral measurement.

Differences among experts for the energy at given wavelengths are considerably greater than for the solar constant.

2.2.1 Johnson Curve (Ground-Based)

The spectral curve most widely accepted in the United States has been that of F.S. Johnson (ref. 17). The basis for various portions of that spectrum is treated briefly in section 2.1.1.1.

2.2.2 Galileo and Eppley-JPL Experiments (High-Altitude)

Measurements of the spectral irradiance curve obtained from the Galileo experiment in 1967 were provided by five instruments aboard the NASA 711 research aircraft (sec. 2.1.2.1). Each of the five instruments was of a different type and is described in table III (ref. 5). A detailed spectral irradiance curve of the Sun resulted from this investigation (refs. 5, 24, and 25).

The 12-channel filter radiometer of the Eppley-JPL experiment also yielded extensive spectral data. In general, the agreement between the Eppley-JPL results and the Galileo experiment was ±5 percent. The mean solar irradiance derived from the two Eppley-JPL control broad bandpass filters (for wavelengths greater than 0.607μm) is 87.4 mW cm^{-2}. This compares with the Galileo value of 86.0 mW cm^{-2} for the same spectral region, a difference of 1.5 percent.

Table III

Spectral Irradiance Instruments Aboard the NASA 711 Aircraft

Instrument	Energy Detector	Type of Instrument	Aircraft Window Material	Wavelength Range (μm)
Perkin - Elmer Monochromator	1P28 Tube Thermocouple	LiF Prism	Sapphire	0.3 - 0.7 0.7 - 4
Leiss Monochromator	EMI 9558 QA PbS Tube	Quartz Double Prism	Dynasil	0.3 - 0.7 0.7 - 1.6
Filter Radiometer	Phototube	Dielectric Thin Films	Dynasil	0.3 - 1.2
P - 4 Interferometer	1P28 or R136 PbS Tube	Soleil Prism	Infrasil	0.3 - 0.7 0.7 - 2.5
I - 4 Interferometer	Thermistor Bolometer	Michelson Mirror	Irtran 4	2.6 - 15

The Eppley-JPL data are referenced to the IPS 56, and the Galileo data to NBS standard lamps and hence to a black body.

2.3 Development of Design Values

2.3.1 Solar Constant

To establish a solar constant value, only high-altitude measurements have been considered because the corrections to ground-based measurements for dust, haze, smoke, and especially water vapor make extrapolation to zero air mass highly uncertain. Table II gives eight values for the solar constant derived from high-altitude measurements.

These eight determinations were evaluated critically to derive a weighted average. Maximum weight (f=10) was given to the values from the Eppley-JPL high-altitude aircraft, Soviet balloon, and JPL Mariner spacecraft because the final values in each case were based on a large mass of data. A high degree of reliability (f=8) was assigned to the values from the NASA 711 aircraft measurements by the cone radiometer and Hy-Cal pyrheliometer for which a large number of data points were considered and carefully extrapolated to zero air mass. The Murcray balloon value (f=4) was given smaller weight because of less data. The two Ångström instruments from NASA 711 aircraft yielded relatively fewer points and hence were given less weight (f=3).

The weighted average yields a solar constant of 135.3 mW cm^{-2} or 1.940 cal cm^{-2} min^{-1} which is adopted herein.

The estimated error is ±2.1 mW cm^{-2} or ±0.03 cal cm^{-2} min^{-1}. This estimate of error, 1.5 percent, is quite conservative because of the large number of high-altitude measurements on which it is based.

The adopted solar constant value is 3 percent lower than the Johnson value of 139.5 mW cm^{-2} or 2.00 cal cm^{-2} min^{-1}, which heretofore has been widely accepted.

2.3.2 Solar Spectral Irradiance

2.3.2.1 Design Values

The recommended values for solar spectral irradiance are derived mainly from the curve resulting from the Galileo experiment with modifications based on the Eppley-JPL results and additions from other sources for the two extreme ends of the spectrum. Figure 1 shows the design curve from 0.2 to 2.6μm, and table V gives the spectrum in tabular form.

In the wavelength range where several of the Eppley-JPL filters are in agreement in showing a slightly different value from that of the Galileo experiment, a weighted average of the two sets of data was taken. This produced a small revision of the Galileo curve in the wavelength range from 0.3 to 0.7μm and increased the integrated value under the curve of the solar constant from 135.1 mW cm^{-2} (obtained from the Galileo experiments given in reference 5) to 135.3 mW cm^{-2}.

In the 0.3 to 2.2μm wavelength range, which contains all but 6.4 percent of solar energy, the spectral data are based on a detailed analysis of many sets of data from a variety of instruments. Therefore, instrumental errors could be used to compensate each other and thus lessen the error in the final weighted average. Hence, it is estimated that the spectral irradiance values in this range have an accuracy of ±5 percent. The uncertainties at the two extreme ends of the spectrum are greater.

In table V the energy in the range 0 to 0.12μm is shown to be nearly 0.0006 mW cm^{-2} on the basis of extensive measurements by Hinteregger (ref. 37). The value for spectral irradiance at 0.12μm is high compared to those at 0.14μm and 0.15μm because of the Lyman α emission line.

In the 0.14 to 0.20μm range, the values published by the Galileo experimenters were based on Naval Research Laboratory (NRL) data (sec.2.2.2). Heath (ref.38) and Parkinson and Reeves (ref. 39) have found the NRL data to be about 2.5 times too high. Hence, the values have been adjusted downwards.

In the range 0.22 to 0.30μm, the values published by the Galileo experimenters have been retained (sec. 2.2.2) because of confirming Nimbus 3 data (ref. 38).

The Eppley-JPL data were used for revision in the range 0.3 to 0.7μm. The maximum changes are + 2.3 percent at 0.34μm -0.7 percent at 0.45μm, and +1.6 percent at 0.63μm. Lesser variations occur at intermediate wavelengths. The Galileo experiment values have been retained in the range 0.7 to 20μm.

A few entries have been added in the range 20 to 1000μm. Irradiance values at these wavelengths have been computed from the combined data on brightness temperature of the Sun from many different authors as quoted by Shimabukoro and Stacey (ref. 40).

The development of the design values is given more detailed treatment in references 41 and 42.

2.3.2.2 Comparison with Other Solar Curves

Figure 2 shows a comparison between the Johnson curve (ref. 17) and the one adopted herein. The X-axis is wavelength in μm and the Y-axis is the ratio of kP'_λ to P_λ where k is a normalizing factor which makes the area under the Johnson curve equal to that under the design curve, P'_λ is the spectral irradiance at a given wavelength for the Johnson curve, and P_λ the spectral irradiance at the same wavelength for the design curve. Figure 2 is a computer-generated plot which shows all variations between the two curves.

Figures 3, 4, 5 and 6 show similar comparisons of four other curves to the adopted curve: figure 3, Nicolet (ref. 14) in the range 0.3 to 2.2μm; figure 4, Labs and Neckel (ref. 7) in the range 0.25 to 2.5μm; figure 5, Stair and Ellis (ref. 20) in the range 0.3 to 0.53μm; and figure 6, Thekaekara, Kruger; and Duncan (refs. 5 and 25), the Galileo experiment, in the range 0.25 to 2.5μm. No normalization factor was used for figure 6; the ordinates give the ratios by which the spectral irradiance values published by the Galileo experimenters were divided to give the design values in table V.

A comparison of figures 2, 3, and 4 shows that in the range 0.25 to 0.45μm, the Johnson values are high and those of Nicolet and the Labs and Neckel values are low compared to the design values. It will be recalled that Johnson had scaled Dunkelman and Scolnik values upward by 8.8 percent. Nicolet and Labs and Neckel values are low, probably because of the difficulty of estimating the true solar continuum in a wavelength range which is so rich in Fraunhofer lines.

Both Nicolet and Labs and Neckel show a sharp change in the ratio near the Balmer discontinuity which is not seen in figures 2 and 5 where the data are based on the irradiance of the whole solar disc rather than on the radiance at the center of the disc.

In the 0.25 to 0.6μm range, the Stair and Ellis curve (fig. 5) claims a higher degree of reliability because the authors used the NBS standard lamp as reference and two types of instruments, a Leiss monochromator and filter radiometer. The excursions above and below design curve values indicated in figure 5 are more or less evenly balanced out in contrast to the consistent deviation from the design curve by Johnson or Labs and Neckel as shown in figures 2 and 4.

In the range 0.5 to 0.7μm where figures 2, 3 and 4 show the ratios >1, the agreement between the Galileo experiment and Eppley-JPL results was so close that revision of the Galileo data did not seem justified beyond what is shown in figure 6.

For wavelengths $>$ 1.0μm, figures 2, 3, and 4 have certain similarities; e.g., each has a peak near 2.0μm. This is so because the three curves to which the design curve is being compared were based on ground-based measurements and so were extrapolated in this range on the assumption of a 6000 K black body curve for the Sun. The Galileo experiment on which the design curve is based gave the first direct and detailed measurements in this range.

3. CRITERIA

The solar constant and related values given in section 3.1 should be used for the design of space vehicles, spacecraft, subsystems, and experiments.

For computations which require solar irradiance data over narrow wavelength bands, the solar spectral irradiance values given in section 3.2 should be used.

3.1 The Solar Constant

The design value of the solar constant is 135.3 mW cm^{-2} or 1.940 cal cm^{-2} min^{-1}. It is taken for a mean Earth-Sun distance of 1 AU equal to 1.496×10^{13} cm and in the absence of the Earth's atmosphere. The estimated error is ±2.1 mW cm^{-2} or ±0.03 cal cm^{-2} min^{-1}. (The calorie is the thermochemical calorie and the milliwatt is 10^{-3} absolute joule per second).

3.1.1 Variation with Earth-Sun Distance

On the basis of the foregoing value adopted for the solar constant, the following values were derived to give variation in total solar irradiance* with changes in Earth-Sun distance during the year. Such variation can be determined with greater accuracy than the absolute value of the solar constant.

Date	Solar Irradiance**
January 3 (perihelion)	139.9 mW cm^{-2}
February 1	139.3
March 1	137.8
April 1	135.5
May 1	133.2
June 1	131.6
July 4 (aphelion)	130.9
August 1	131.3
September 1	132.9
October 1	135.0
November 1	137.4
December 1	139.2

3.1.2 Energy Values at Planetary Distances

Table IV gives solar irradiance values for the other planets of the solar system on the basis of the solar constant adopted herein and references 43 and 44.

* The term total solar irradiance refers to total radiant energy received at a given distance whereas the term solar constant describes the same parameter at 1 AU.

** The changes in Sun-Earth distance for the same date from year to year are such that values may vary by ±0.1 mW cm^{-2}. For precise comparison, the table of radius vector given in the American Ephemeris (ref. 43) should be consulted.

3.2 Solar Spectral Irradiance

The spectral irradiance of the Sun at the distance of 1 AU in the absence of the Earth's atmosphere is given in table V and figure 1. The estimated error in these values is ±5 percent in the wavelength range of 0.3 to 3.0μm. Outside these wavelength limits, the uncertainties are greater.

All values are for a mean Earth-Sun distance of 1.496×10^{13} cm. Astrophysical constants for derivation of values at other distances are given in appendix A.

In the 0.3 to 0.75μm range, the value of P_λ (in table V) for each wavelength is the average irradiance for a 100Å bandwidth centered at that wavelength. This gives a solar irradiance independent of the detailed Fraunhofer structure which each instrument displays in a different way according to its wavelength resolution. In the range beyond 0.75μm where the Fraunhofer structure is small and the wavelength resolution becomes less, wider bandwidths are used for averaging, 500 Å for 0.75 to 1.0μm and 1000 Å for 1.0 to 5.0μm.

Extension of the extraterrestrial spectrum to the X-ray range and microwave range is given in appendix B.

Table IV

Orbital Constants of the Planets and Solar Irradiance at Planetary Distances

Planet	Semi-Major Axis of Orbit		Sidereal Period (days)	Eccentricity of Orbit 1971 (ϵ)	Solar Irradiance at Distance of Semi-Major Axis*		Ratio of Max to Min Irradiance** $\left(\frac{1+\epsilon}{1-\epsilon}\right)^2$
	(AU)	(10^6 km)			Solar Constant	mW cm^{-2}	
Mercury	0.387 099	57.91	87.9686	0.205 629	6.673 5	902.9	2.303
Venus	0.723 332	108.21	224.700	0.006 787	1.911 3	258.6	1.028
Earth	1.000	149.60	365.257	0.016 721	1.000 0	135.3	1.069
Mars	1.523 69	227.94	686.980	0.093 379	0.430 7	58.28	1.454
Jupiter	5.2028	778.3	4 332.587	0.048 122	0.036 95	4.999	1.212
Saturn	9.540	1427	10 759.20	0.052 919	0.010 99	1.487	1.236
Uranus	19.18	2869	30 685	0.049 363	0.002 718	0.3678	1.218
Neptune	30.07	4498	60 188	0.004 362	0.001 106	0.1496	1.018
Pluto	39.44	5900	90 700	0.252 330	0.000 643	0.0870	2.806

*Solar irradiance is $\frac{1}{R^2}$ in units of the solar constant and $\frac{135.3}{R^2}$ in mW cm^{-2} where R is the semi-major axis of the planetary orbit.

**Values of eccentricity change with time; the ratio of solar irradiance at perihelion to that at aphelion in the last column is computed on the assumption of constant eccentricity.

TABLE V

Solar Spectral Irradiance at 1 AU (Solar Constant of 135.30mWcm^{-2})

Wavelength, λ (μm)	Average Irradiance*, P_λ (W cm^{-2} μm^{-1})	Area under curve, 0 to λ, A_λ (mW cm^{-2})	Portion of solar constant with wavelength < λ, D_λ (%)
0.120	0.000010	0.00059993	0.00044
0.140	0.000003	0.00073000	0.00054
0.150	0.000007	0.00072000	0.00058
0.160	0.000023	0.00093000	0.00069
0.170	0.000063	0.00135000	0.00101
0.180	0.000125	0.00230000	0.00170
0.190	0.000271	0.00428000	0.00316
0.200	0.00107	0.010985	0.0081
0.210	0.00229	0.027785	0.0205
0.220	0.00575	0.067985	0.0502
0.225	0.00649	0.098585	0.0729
0.230	0.00667	0.131485	0.0972
0.235	0.00593	0.162985	0.1205
0.240	0.00630	0.193560	0.1430
0.245	0.00723	0.227385	0.1681
0.250	0.00704	0.263060	0.1944
0.255	0.0104	0.306660	0.2267
0.260	0.0130	0.365160	0.270
0.265	0.0185	0.443910	0.328
0.270	0.0232	0.548160	0.405
0.275	0.0204	0.657160	0.486
0.280	0.0222	0.763660	0.564
0.285	0.0315	0.897910	0.644
0.290	0.0482	0.09716	0.811
0.295	0.0584	1.36366	1.008
0.300	0.0514	1.63816	1.211
0.305	0.0603	1.91741	1.417
0.310	0.0689	2.24041	1.656
0.315	0.0764	2.60366	1.924
0.320	0.0830	3.00216	2.219
0.325	0.0975	3.45341	2.552
0.330	0.1059	3.96191	2.928
0.335	0.1061	4.49691	3.324
0.340	0.1074	5.03566	3.722
0.345	0.1069	5.57141	4.118
0.350	0.1093	6.11191	4.517
0.355	0.1083	6.65591	4.919
0.360	0.1068	7.19366	5.317
0.365	0.1132	7.74366	5.723
0.370	0.1181	8.32191	6.151
0.375	0.1157	8.90641	6.583
0.380	0.1120	9.47566	7.003
0.385	0.1098	10.0302	7.413
0.390	0.1098	10.5792	7.819
0.395	0.1189	11.1509	8.242
0.400	0.1429	11.8054	8.725
0.405	0.1644	12.5737	9.293
0.410	0.1751	13.4224	9.920
0.415	0.1774	14.3037	10.572
0.420	0.1747	15.1839	11.222

Wavelength, λ (μm)	Average Irradiance*, P_λ (W cm^{-2} μm^{-1})	Area under curve, 0 to λ, A_λ (mW cm^{-2})	Portion of solar constant with wavelength < λ, D_λ (%)
0.425	0.1693	16.0439	11.858
0.430	0.1639	16.8769	12.474
0.435	0.1663	17.7024	13.084
0.440	0.1810	18.5707	13.726
0.445	0.1922	19.5037	14.415
0.450	0.2006	20.4857	15.141
0.455	0.2057	21.5014	15.892
0.460	0.2066	22.5322	16.653
0.465	0.2048	23.5607	17.414
0.470	0.2033	24.5809	18.168
0.475	0.2044	25.6002	18.921
0.480	0.2074	26.6297	19.682
0.485	0.1976	27.6422	20.430
0.490	0.1950	28.6237	21.156
0.495	0.1960	29.6012	21.878
0.500	0.1942	30.5767	22.599
0.505	0.1920	31.5422	23.313
0.510	0.1882	32.4927	24.015
0.515	0.1833	33.4214	24.702
0.520	0.1833	34.3379	25.379
0.525	0.1852	35.2592	26.060
0.530	0.1842	36.1827	26.743
0.535	0.1818	37.0977	27.419
0.540	0.1783	37.9979	28.084
0.545	0.1754	38.8822	28.738
0.550	0.1725	39.7519	29.381
0.555	0.1720	40.6132	30.017
0.560	0.1695	41.4669	30.648
0.565	0.1705	42.3169	31.276
0.570	0.1712	43.1712	31.908
0.575	0.1719	44.0289	32.542
0.580	0.1715	44.8874	33.176
0.585	0.1712	45.7442	33.809
0.590	0.1700	46.5972	34.440
0.595	0.1682	47.4427	35.065
0.600	0.1666	48.2797	35.683
0.605	0.1647	49.1079	36.296
0.610	0.1635	49.9284	36.902
0.620	0.1602	51.5469	38.098
0.630	0.1570	53.1329	39.270
0.640	0.1544	54.6899	40.421
0.650	0.1511	56.2174	41.550
0.660	0.1486	57.7159	42.658
0.670	0.1456	59.1869	43.745
0.680	0.1427	60.6284	44.810
0.690	0.1402	62.0429	45.856
0.700	0.1369	63.4284	46.880
0.710	0.1344	64.7849	47.882
0.720	0.1314	66.1139	48.865
0.730	0.1290	67.4159	49.827

*Spectral irradiance averaged over small bandwidth centered at λ:

0.3 to 0.75 μm (bandwidth, 100 Å)

0.75 to 1.0 μm (bandwidth, 500 Å)

1.0 to 5.0 μm (bandwidth, 1000 Å)

TABLE V (continued)

Wavelength, λ (μm)	Average Irradiance*, P_λ ($W\ cm^{-2}\mu m^{-1}$)	Area under curve, 0 to λ, A_λ ($mW\ cm^{-2}$)	Portion of solar constant with wavelength < λ, D_λ (%)
0.740	0.1260	68.6909	50.769
0.750	0.1235	69.9384	51.691
0.800	0.1107	75.7934	56.019
0.850	0.0988	81.0309	59.890
0.900	0.0889	85.7234	63.358
0.950	0.0835	90.0334	66.544
1.000	0.0746	93.9859	69.465
1.100	0.0592	100.676	74.409
1.200	0.0484	106.056	78.386
1.300	0.0396	110.456	81.638
1.400	0.0336	114.116	84.343
1.500	0.0287	117.231	86.645
1.600	0.0244	119.886	88.607
1.700	0.0202	122.116	90.256
1.800	0.0159	123.921	91.590
1.900	0.0126	125.346	92.643
2.000	0.0103	126.491	93.489
2.100	0.0090	127.456	94.202
2.200	0.0079	128.301	94.827
2.300	0.0068	129.036	95.370
2.400	0.0064	129.696	95.858
2.500	0.0054	130.286	96.294
2.600	0.0048	130.796	96.671
2.700	0.0043	131.251	97.007
2.800	0.00390	131.661	97.3104
2.900	0.00350	132.031	97.5838
3.000	0.00310	132.361	97.8277
3.100	0.00260	132.646	98.0384
3.200	0.00226	132.889	98.2180
3.300	0.00192	133.098	98.3724
3.400	0.00166	133.277	98.5047
3.500	0.00146	133.433	98.6200
3.600	0.00135	133.573	98.7239
3.700	0.00123	133.702	98.8192
3.800	0.00111	133.819	98.9057
3.900	0.00103	133.926	98.9848
4.000	0.00095	134.025	99.0580
4.100	0.00087	134.116	99.1252
4.200	0.00078	134.199	99.1862
4.300	0.00071	134.273	99.2412
4.400	0.00065	134.341	99.2915
4.500	0.00059	134.403	99.3373
4.600	0.00053	134.459	99.3787
4.700	0.00048	134.510	99.4160
4.800	0.00045	134.556	99.4504
4.900	0.00041	134.599	99.482195
5.000	0.0003830	134.63906	99.511500
6.000	0.0001750	134.91806	99.717709
7.000	0.0000990	135.05506	99.818965
8.000	0.0000600	135.13456	99.877724
9.000	0.0000380	135.18356	99.913939
10.000	0.0000250	135.21506	99.937221
11.000	0.0000170	135.23606	99.952742
12.000	0.0000120	135.25056	99.963459
13.000	0.0000087	135.26091	99.971109
14.000	0.0000055	135.26801	99.976356
15.000	0.0000049	135.27321	99.980200
16.000	0.0000038	135.27756	99.983415
17.000	0.0000031	135.28101	99.985965
18.000	0.0000024	135.28376	99.987997
19.000	0.0000020	135.28596	99.989623
20.000	0.0000016	135.28776	99.990953
25.000	0.000000610	135.29328	99.995037
30.000	0.000000300	135.29556	99.996718
35.000	0.000000160	135.29671	99.997568
40.000	0.000000094	135.29735	99.998038
50.000	0.000000038	135.29801	99.998525
60.000	0.000000019	135.29829	99.998736
80.000	0.000000007	135.29855	99.998928
100.000	0.000000003	135.29865	99.999002
1000.000	0.000000000	135.30000	100.000000

*Spectral irradiance averaged over small bandwidth centered at λ:

0.3 to 0.75 μm (bandwidth, 100 Å)

0.75 to 1.0 μm (bandwidth, 500 Å)

1.0 to 5.0 μm (bandwidth, 1000 Å)

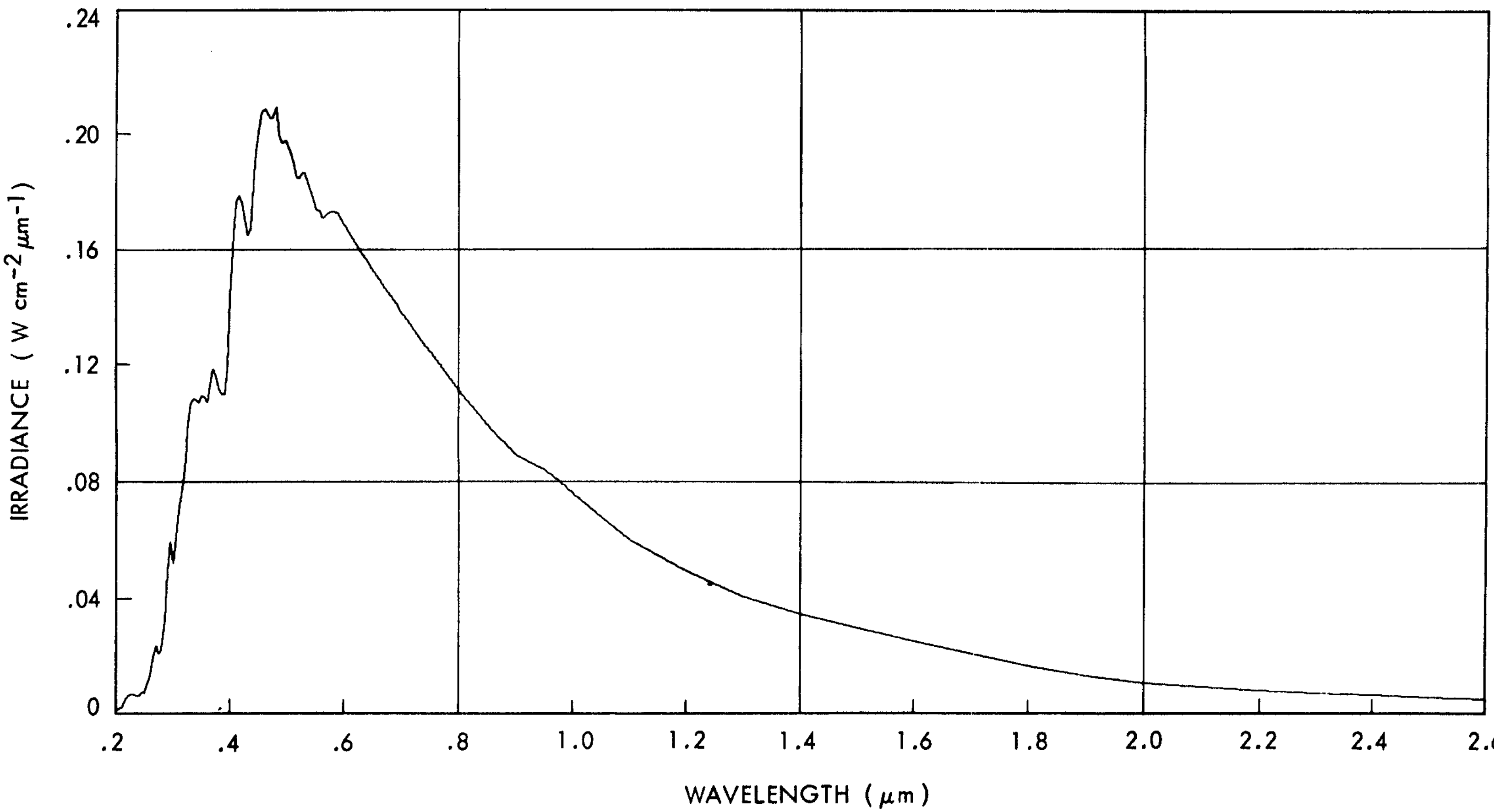

Figure 1. - Solar Spectral Irradiance.

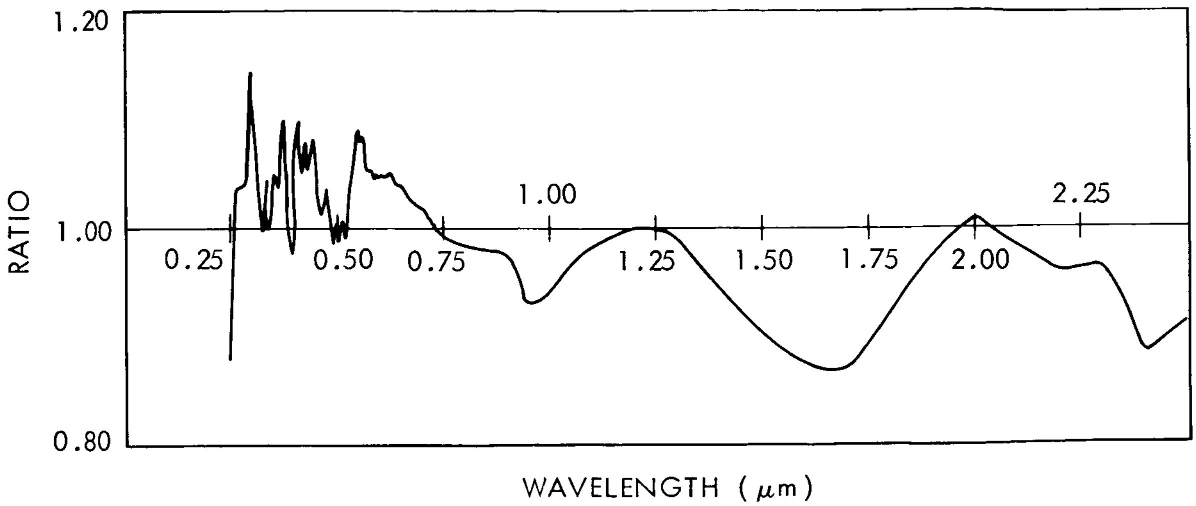

Figure 2. - Comparison of Design Values and Johnson Data for Solar Spectral Irradiance. (Curve shows ratio of Johnson values, normalized per section 2.3.2.2, to design values.)

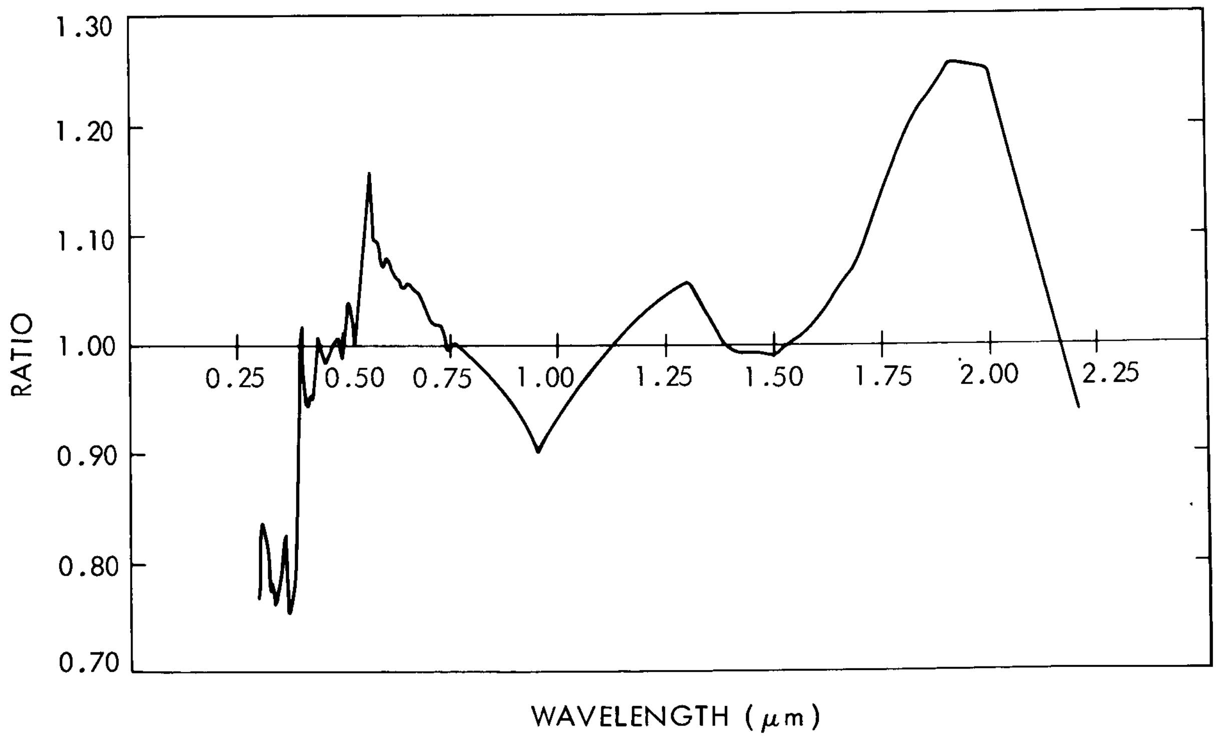

Figure 3. - Comparison of Design Values and Nicolet Data for Solar Spectral Irradiance. (Curve shows ratio of Nicolet values, normalized per section 2.3.2.2, to design values.)

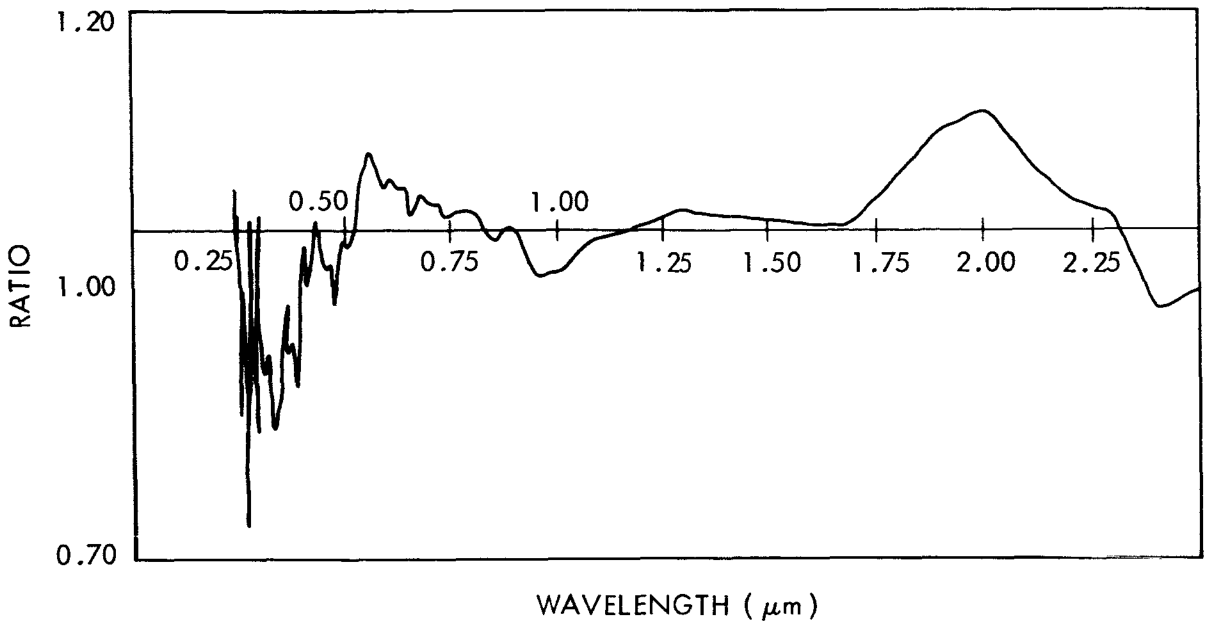

Figure 4. - Comparison of Design Values and Labs and Neckel Data for Solar Spectral Irradiance. (Curve shows ratio of Labs and Neckel values, normalized per section 2.3.2.2, to design values.)

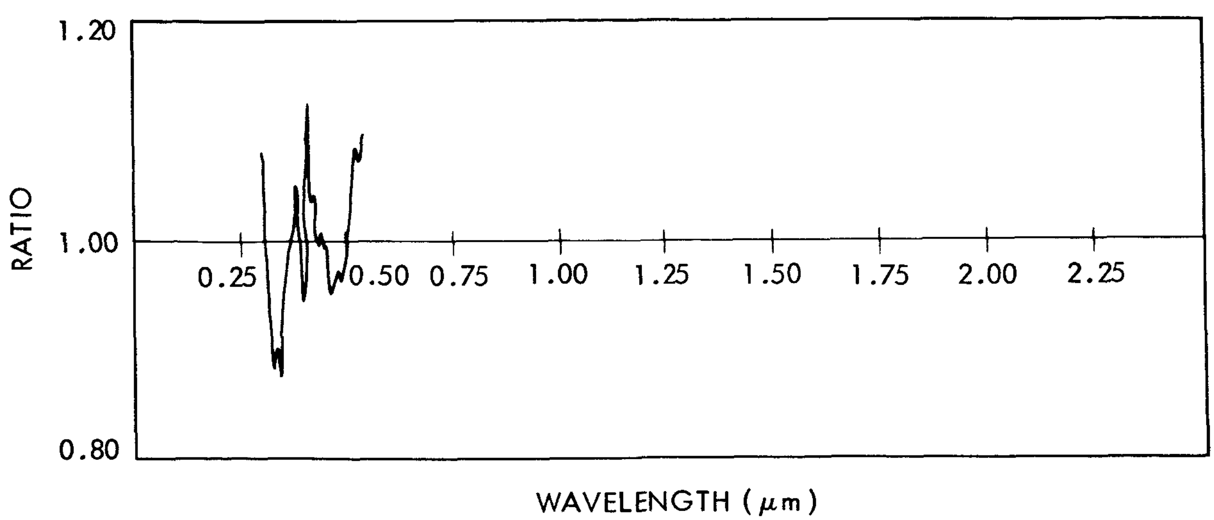

Figure 5. - Comparison of Design Values to Stair and Ellis Data for Solar Spectral Irradiance. (Curve shows ratio of Stair and Ellis values, normalized per section 2.3.2.2, to design values.)

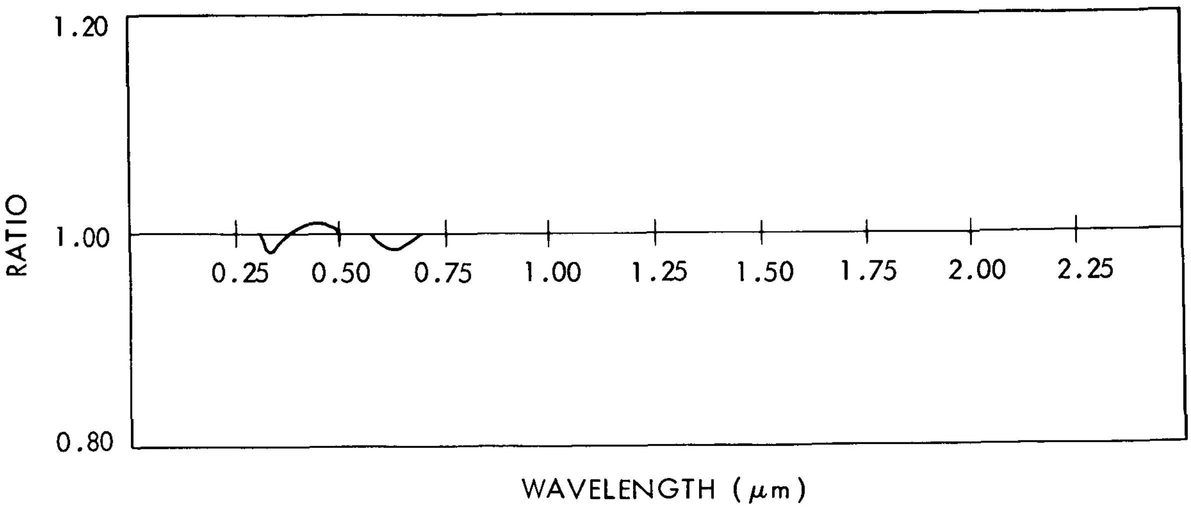

Figure 6. - Ratio of values from the Galileo Experiment to Design Values for Solar Spectral Irradiance.

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APPENDIX A

CONSTANTS AND EQUATIONS RELATED TO SOLAR ELECTROMAGNETIC RADIATION

A.1 Conversion Factors

Solar Constant $= 135.3$ mW cm^{-2}
$= 0.1353$ W cm^{-2}
$= 1353$ W m^{-2}
$= 1.353 \times 10^{6}$ erg cm^{-2} sec^{-1}
$= 125.7$ W ft^{-2}
$= 1.940$ cal cm^{-2} min^{-1}
$= 0.032\ 3$ cal cm^{-2} sec^{-1}
$= 429.2$ Btu ft^{-2} hr^{-1}
$= 0.119$ Btu ft^{-2} sec^{-1}
$= 1.937$ Langleys min^{-1}

The calorie is the thermochemical calorie-gram and is defined as 4.1840 absolute joules. The Btu is the thermochemical British thermal unit and is defined by the relationship: 1 Btu (thermochemical)/(°F x lb) = 1 cal g (thermochemical)/(°C x g) (ref. 6, Zimmerman and Lavine, pp. xiv,xv).

The Langley, however, is defined in terms of the older thermal unit the calorie gm (mean), i.e., 1 Langley = 1 cal g (mean) cm^{-2}; 1 cal g (mean) = 4.190 02 joules.

Mean solar energy received by the Earth-atmosphere system per year $S_y = 5.445 \times 10^{24}$ joules
$= 1.301 \times 10^{24}$ cal

This value is obtained from the equation

$$S_y = SN\pi r_e^2$$

where S is the solar constant (Wcm^{-2}), N is the number of seconds in a sidereal year ($3.155\ 815 \times 10^{7}$ sec), and r_e is the mean radius of the Earth ($6.371\ 03 \times 10^{8}$ cm).

Rate of energy radiated by the Sun is obtained by multiplying the solar constant by the surface area of a sphere of radius 1 AU and is equal to 3.805×10^{26} watts. This rate of radiation is equivalent to a loss of mass, according to the equation $E = mc^2$, of 4.234×10^{12} g sec^{-1} or 4.670 million tons per second.

A.2 Temperature of the Sun's Photosphere

Effective black body temperature of the Sun equals 5630.7 K. The effective black body temperature is that temperature of the normalized black body curve (normalized so that the area under the curve is equal to the solar constant) for which the area enclosed between the black body curve and the design curve (table V) is a minimum.

The irradiance of the normalized black body curve is computed by equation

$$P_\lambda = \frac{C_1}{\lambda^5 \left(e^{C_2/\lambda T} - 1\right)} \qquad (1)$$

where λ is wavelength in μm, T is temperature 5630.7 K, C_2 =14380.0, and C_1 is the normalizing constant equal to 0.885 064 26.

The temperature of the Sun computed from Wien's displacement law, $T\lambda_{max} = C$, is 6166K. λ_{max} of the solar spectrum which cannot be clearly defined because of Fraunhofer absorption is taken to be 0.47 μm. The Wien constant is 0.28978 cm deg.

The temperature of the Sun is 5762 K as computed by the Stefan-Boltzmann equation

$$S = \sigma T^4 r^2 / R^2$$

where

the solar constant, S = 135.3mW cm^{-2}
the Stefan-Boltzmann constant, $\sigma = 5.669\,2 \times 10^{-5}$ erg cm^{-2} deg^{-4} sec^{-1}
the radius of the solar disc, $r = 6.9698 \times 10^{10}$ cm
the mean Earth-Sun distance, $R = 1.495\,985 \times 10^{13}$ cm
(Limb darkening is ignored)

The brightness temperature of the Sun for a given wavelength can be computed by transforming equation (1) to the form

$$T = \frac{C_2}{\lambda \log_e \left(\frac{C_1}{\lambda^5 P_\lambda} + 1 \right)} \qquad (2)$$

where C_2 is the second radiation constant, C_1 is $2\pi hc^2 r^2/R^2$, and P_λ is irradiance at wavelength λ as given in table V. The Constants C_1 and C_2 with suitable scaling for P_λ in $Wcm^{-2}\mu m^{-1}$ and λ in μm are $C_1 = 0.809748$ and $C_2 = 14380.0$.

The brightness temperature of the Sun which is relatively high in the X-ray range drops to a minimum of about 4540 K at 0.15μm; it rises to a high value near 6000 K in the visible and near IR; in the IR the temperature falls slowly, reaching a minimum of about 4360 K near 50μm, and then rises to relatively higher values in the microwave region.

APPENDIX B

THE SOLAR SPECTRUM FROM X-RAYS TO RADIO WAVES

The solar electromagnetic spectrum over the wavelength range 10 Å to 10 meters is shown in Figure 7. The X-axis shows the wavelength and associated frequency. The Y-axis gives the solar spectral irradiance at a distance of one AU in the absence of the Earth's atmosphere. Both X- and Y-axis are in log scale. For the wavelength range above 40μm the range of values on the Y-axis changes three times, each time by six decades.

The spectral irradiance in the wavelength range 0.14 to 20 μm is based on the design values given in table V. Other sources are used for $\lambda < 0.14\ \mu$m and $\lambda > 20\mu$m.

The spectral irradiance from a black body of the same radius as the Sun at the distance of 1 AU is shown by the dashed curve. Over most of the spectral range the temperature chosen for the black body curve is 5762 K. This is the temperature derived from the Stefan-Boltzmann equation corresponding to a solar constant value of 135.3 mW cm^{-2}. At the two extreme ends of the spectrum other values of temperature more closely related to the brightness temperature have been used.

The spectral irradiance values in the range $\lambda < 0.14\mu$m are based on Hinteregger's data (ref. 37). In this range the solar spectrum consists of a large number of narrow emission lines superposed on a relatively weak continuum. Because this detailed structure cannot be shown adequately on the highly reduced wavelength scale of figure 7, the energy has been integrated over narrow bands each of 50 Å width. The irradiance values seem to change considerably during the solar cycle. Those given here are for medium solar activity.

In the range 20μm to 0.6 cm, the spectral curve has been computed from the values of brightness temperature quoted by Shimabukoro and Stacey (ref. 40). An average wavelength dependent brightness temperature has been derived from the best available information, and at each wavelength the corresponding irradiance has been computed from Planck's equation.

For the microwave and radio range of $\lambda > 0.6$ cm, the values listed by Allen (ref. 43, p. 188) have been used and curves have been drawn for four different types of solar energy emission.

In table VI are given the values of spectral irradiance at the two ends of the solar spectrum outside the range covered in table V. For most of the wavelength range the corresponding brightness temperature also has been listed.

TABLE V

Solar Spectral Irradiance

X-ray, UV Range

Wavelength (μm)	Spectral Irradiance (W cm $^{2}\mu m^{-1}$)	Brightness Temperature (degrees Kelvin)
0.005	2.24×10^{-6}	69200
0.01	1.78×10^{6}	37500
0.015	2.76×10^{-6}	26730
0.02	9.70×10^{-6}	21670
0.025	4.72×10^{-6}	17550
0.03	1.68×10^{-6}	14570
0.035	1.188×10^{-5}	13620
0.04	3.4×10^{-7}	11690
0.045	4.0×10^{7}	10650
0.05	1.0×10^{6}	10070
0.055	3.2×10^{7}	8945
0.06	1.38×10^{-6}	8768
0.065	8.2×10^{7}	8058
0.07	2.4×10^{7}	7256
0.75	4.4×10^{7}	7007
0.8	8.4×10^{7}	6811
0.85	1.62×10^{6}	6652
0.9	2.14×10^{6}	6425
0.95	9.4×10^{7}	5954
0.1	2.26×10^{6}	5920
0.105	3.88×10^{6}	5827
0.11	1.36×10^{6}	5375
0.115	1.16×10^{-6}	5155
0.12	8.67×10^{5}	6073
0.125	1.52×10^{-6}	4881
0.13	1.2×10^{6}	4685
0.14	3.0×10^{6}	4601
0.15	7.0×10^{-6}	4536
0.16	2.3×10^{-5}	4581
0.17	6.3×10^{-5}	4620

IR, Microwave Range

Wavelength (μm)	Spectral Irradiance (W cm $^{-2}\mu m^{-1}$)	Brightness Temperature (degrees Kelvin)
20.0	1.60×10^{-6}	4900
25.0	6.10×10^{-7}	4515
30.0	3.00×10^{-7}	4550
35.0	1.6×10^{7}	4470
40.0	9.41×10^{-8}	4455
50.0	3.80×10^{8}	4360
60.0	1.92×10^{8}	4530
80.0	6.45×10^{9}	4780
100.0	2.66×10^{-9}	4800
120.0	1.29×10^{-9}	4825
150.0	5.34×10^{-10}	4845
200.0	1.71×10^{-10}	4885
250.0	7.04×10^{-11}	4915
300.0	3.42×10^{-11}	4950
400.0	1.10×10^{11}	5005
500.0	4.55×10^{12}	5060
600.0	2.22×10^{12}	5120
800.0	7.13×10^{-13}	5195
1000.0	2.97×10^{13}	5280
1200.0	1.46×10^{13}	5370
1500.0	6.10×10^{-14}	5490
2000.0	2.00×10^{-14}	5675
2500.0	8.43×10^{-15}	5850
3000.0	4.10×10^{-15}	5900
4000.0	1.32×10^{15}	6000
5000.0	5.58×10^{-16}	6200

Microwave, Radio Range

Wavelength (cm)	Spectral Irradiance		W cm $^{-2}\mu m^{-1}$	
	Sunspot Maximum	Sunspot Minimum	Typical Noise Storm	Typical Outburst
0.6	2.83×10^{-16}	2.83×10^{16}		
1.5	1.09×10^{17}	9.73×10^{-18}		
3.0	1.13×10^{-18}	8.67×10^{-19}		6.67×10^{-20}
6.0	1.29×10^{-19}	9.58×10^{-20}		4.16×10^{-20}
15.0	9.20×10^{-21}	6.53×10^{21}		1.33×10^{20}
30.0	1.47×10^{-21}	9.00×10^{-22}	0	6.67×10^{-21}
60.0	2.41×10^{-22}	1.50×10^{-22}	4.17×10^{-23}	2.50×10^{-21}
150.0	1.25×10^{-23}	9.2×10^{24}	9.33×10^{-23}	5.33×10^{-22}
300.0	7.67×10^{-25}	6.0×10^{-25}	3.33×10^{-23}	1.67×10^{-22}
600.0	4.08×10^{-26}	3.0×10^{26}	5.83×10^{-24}	4.17×10^{-23}

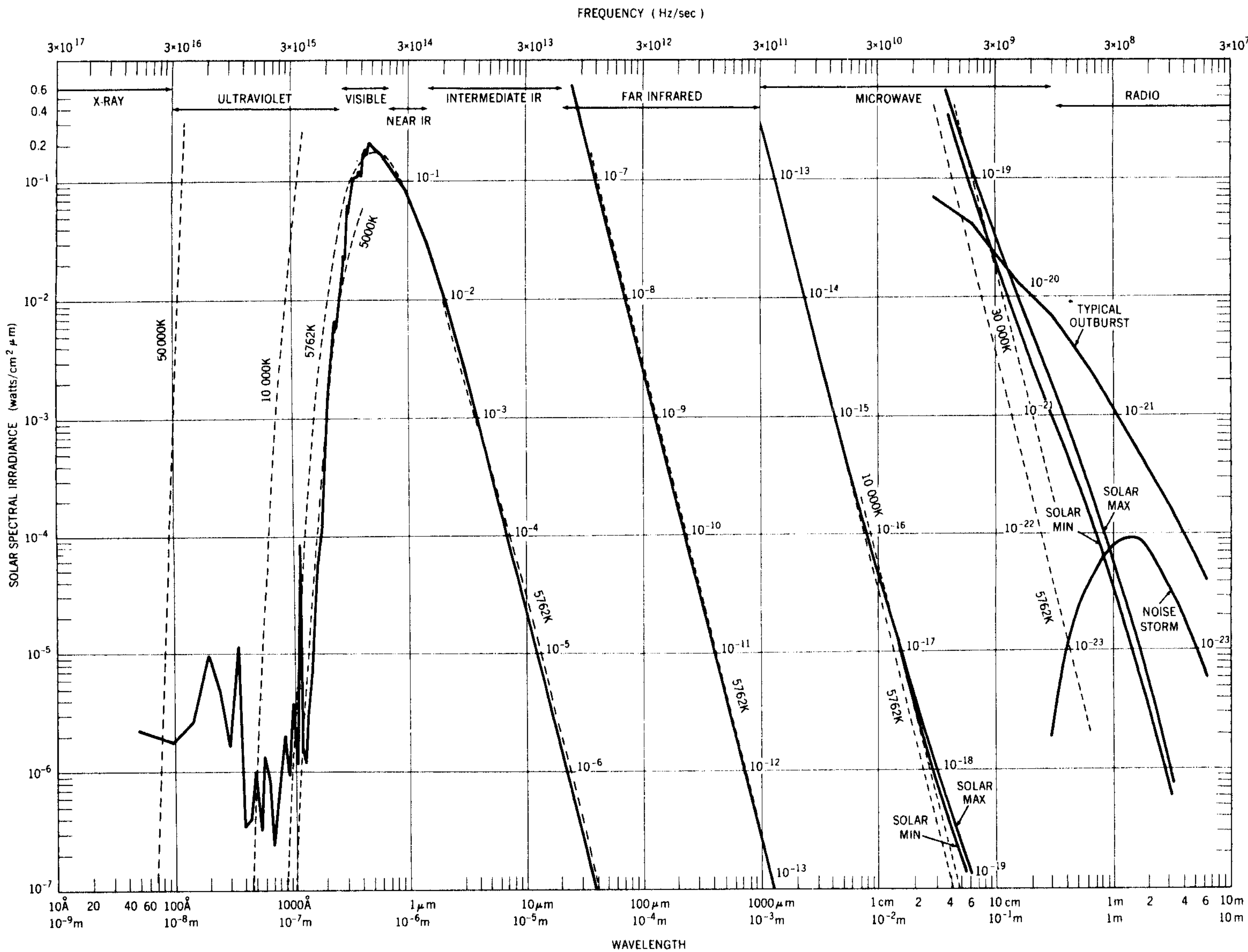

Figure 7. - The Solar Electromagnetic Spectrum.

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